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Wave energy status in Asia

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ABSTRACT

Climate change can bring about destructive effects (e.g., rising temperatures, heavy rains and droughts) to countries worldwide, severely influencing future growth and degrading the quality of life. Asia, which is home to the majority of the world's population, is particularly vulnerable to these impacts. Asian countries are responsible for more than half of the global CO_2 output and renewable energy production is limited. Unabated climate change may endanger previous economic developments and place the region's future at serious risk. Therefore, there is a clear need to increase the share of renewable energy via various sources. Importantly, the continent has extensive coastlines, with abundant wave energy in many areas. The main objectives of this study are to review the current status of wave energy in Asia and to provide an overview of the areas that may be considered for future development. For this purpose, Asia is divided into four regions: East, Southeast, South and West. Active wave energy projects are highlighted, and the wave energy potential is discussed country by country based on the data available in the literature, including suggested sites for development.

1. Introduction

Fossil fuels, e.g. coal, petroleum oil and natural gas, have largely powered development in the past two centuries. Although the world still relies heavily on fossil fuels, ever-increasing concerns have emerged over future supply limitations, climate change, air pollution, and greenhouse-gas emission caused by these fuels (Yousefi et al., 2017). Additionally, the atmospheric concentration of CO_2, one of the most important anthropogenic greenhouse gases, has increased 87% over the last century (Seip and Wenstop, 2006; Le Quéré et al., 2012; Alvarez-Guerra et al., 2012). On average, the increase in CO_2 will result in increased global temperatures, which will enhance glacier and ice sheet melting, thermally expand ocean water and raise sea levels (IPCC Fifth Assessment Report, 2014). Further, extreme weather events such as typhoons and hurricanes are becoming more common in some regions of the world, while other regions experience more extreme droughts and heat waves (Global Climate Change. Available from: https://climate.nasa.gov). The warmer ocean waters also affect corals by prompting coral bleaching events and altering ocean chemistry. These impacts influence corals and the many organisms that use coral reefs as habitat (Hughes et al., 2017). Moreover, the severity of these changes increases as global temperatures continue to increase, which is attributed to human activities (e.g. human activity is responsible for 97% of climate-warming trends over the past century; Global Climate Change, 2018). Based on current trends and statistical data, as depicted in Fig. 1, CO_2 emissions have increased 194.3% from 1965 to 2016, based on CO_2 production growth from 11357.8 million tonnes in 1965–33432.4 million tonnes in 2016, as indicated in Fig. 2. In addition, the CO_2 production increase of the Middle East and Asia Pacific is more evident than that of other continents. The Middle East and Asia Pacific have the greatest percentage increase of 1448.6% and 1026.7%, respectively (Fig. 3). The graph of CO_2 production from 2014 to 2017 (Fig. 4) highlights the fact that more than half of the CO_2 emissions worldwide are caused by the Middle East and Asia Pacific.

The development of new energy technologies may assist in overcoming fossil fuel exhaustion, environmental issues, security of supply and job creation (Pecher and Kofoed, 2017). In recent years, significant R & D activities have focused on Renewable Energy, including solar, wind, wave, etc. This is because of two interrelated factors: (1) the higher energy potential of these resources; and (2) the commitment of different countries to reduce their CO_2 emissions (Markandya et al., 2016). In addition, some efforts made or being made by countries to increase their share of renewable energy have included feed-in tariffs (Astariz et al., 2015). More generally, incentives play a fundamental

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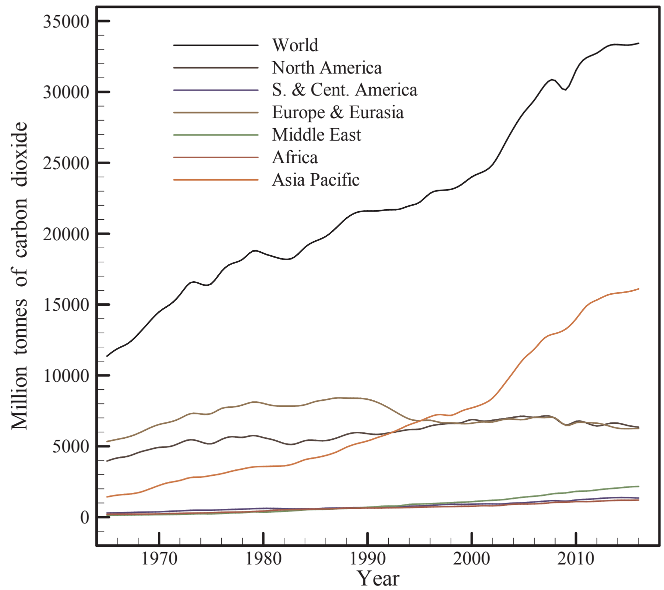


Fig. 1. CO_2 production from 1965 to 2016 by region (BP Statistical Review of World Energy, 2018).

role in the development of renewable energy, especially in the initial phases of exploitation of a particular renewable source, when the corresponding industrial sector is still maturing.

Fig. 5 shows the amount of the renewable energy consumption by region in 2017. As illustrated, the total renewable energy consumption in the world is 485.9 million tonnes of oil equivalent (MTOE), whereas the Middle East and Asia Pacific are about 176.5 MTOE, i.e. approximately a third of the world's renewable energy consumption. This is despite the fact that the CO_2 production in the two regions is more than half of the world. It may be inferred that although there are various sources of renewable energy in these regions, very few of them are sustained, so that the CO_2 emission per capita has only dropped by about 0.4 pc in 2016 – even though the annual growth of renewable energy consumption is about 42 pc and 28 pc for the Middle East and Asia Pacific regions, respectively (World Energy Outlook, 2017).

As the largest continent, Asia is potentially rich in renewable energies. One of the potential renewable energy sources that can be harnessed in this region is wave energy. Wave energy offers several advantages, including being sustainable, abundant, widely available and more easily predictable than alternative energy sources. As a renewable resource it also reduces overall dependency on fossil fuels, and thus helps to curb carbon emissions.

The global energy demand is predicted to rise by 30% by 2040, which is the equivalent of adding another China and India to the worldwide demand today. (World Energy Outlook, 2017). Asia emits the most greenhouse gases of all the major regions in the world, while its energy demand is growing at an alarming rate, greater than the global rate. In addition, several other factors call for a shift towards sustainable energy sources, such as rapid economic growth, growing environmental repercussions, low rural electrification levels and heavy reliance on fossil fuels. Owing to the fact that Asia is surrounded by the Pacific Ocean on the east, the Indian Ocean on the south and the Arctic Ocean on the north as well as containing numerous seas – including the Persian gulf, Oman Sea, Sea of Galilee Andaman Sea, Banda Sea, Barents Sea Bering Sea, Black Sea, Caspian Sea, Chukchi Sea, East China Sea, East Siberian Sea, Java Sea, Kara Sea, Laccadive Sea, Laptev Sea, Red Sea, Sea of Japan, Sea of Okhotsk, South China Sea and Yellow Sea – there is massive potential for capturing wave energy. However, a detailed wave energy assessment is required to determine wave energy opportunities across Asia.

Available wave resource assessment methods include numerical simulation models and ocean measurements (Dalton et al., 2016). Since the latter are expensive and cannot be undertaken without detailed wave buoy data from several locations, a growing tendency is to use numerical wave models as a first pass assessment (Lavidas et al., 2017). Due to significant advances in computing power, the prediction of mean annual wave power can be made via numerical simulations (Folley, 2016). This approach makes it possible to examine various wave conditions and carry out a wide number of tests at a lower cost than broad acre field measurements (Lopez et al., 2014). The wave data obtained through these numerical models provides an opportunity to better map the wave energy assessment, offering an insight on waver power availability for regional and local scales and giving estimates of wave energy flux to design and employ appropriate wave energy converters (WECs) (Besio et al., 2016; Carballo et al., 2015; Contestabile et al., 2016; Lopez et al., 2015a, 2015b; Vicinanza et al., 2013). A review of all types of WECs is presented by Antonio (2010).

This paper presents a review of renewable wave energy sources as an alternative to fossil fuels in Asia. Furthermore, the wave energy potential of the different countries is investigated by considering the current status of wave energy, presenting the ongoing projects, and proposing appropriate sites for wave farm development. To serve this purpose, the continent is divided up to various sub-regions including East Asia, South Asia, Southeast Asia, and West Asia, with countries categorized in relevant sub-regions. Finally, data is presented to indicate the current status of wave energy in each of these sub-regions to assist researchers and practitioners in finding gaps and directions for future works.

2. Wave energy resources in Asian countries

In this section, a comprehensive review of the potential of wave energy resources is presented for Asian countries, categorized in different sub-regions, which have data available to be studied and analyzed. These countries are examined in alphabetical order of sub-regions. These sub-regions along with the countries are depicted in Fig. 6. Other Asian countries which have coastlines (e.g., Philippines and Singapore), and are omitted in this section have very limited publications in the literature, requiring further attention. The collated data provided here are useful in a preliminary assessment of the wave energy resource in the regions, and thus for wave energy development across the continent.

2.1. East Asia

East Asia has a population of more than 1.64 billion people, representing 22% of the world's population and 38% of Asia's. For this sub-region, the wave energy potential of China, Japan, Korea, and Taiwan (Fig. 6) are reviewed.

2.1.1. China

Known as the world's most populous and also world's fourth-largest country by land area, China is the greatest energy consumer and emitter of greenhouse gases globally (Liu, 2017). This is primarily due to the unbalanced coal-based structure of energy use in the country, which reduces energy efficiency. Further, the energy consumption of the country per GDP is three-fold higher than the world's average. As such, China faces global pressure to reduce the use of fossil fuels and CO_2 emission by accelerating the process of providing energy from clean renewable energy resources (Zhao and Luo, 2017). According to the State Oceanic Administration of China, nearly half of the energy demand of the country can be met by extracting wave energy from its 18,000 km border with the Yellow Sea, Bohai Sea, East China Sea and South China Sea (Zhang et al., 2009). As Zhang et al. (2009) suggests that the oil, natural gas and coal resources of China will be exhausted by 2040, 2060 and 2300, respectively, generating power from waves is a promising option to satisfy the power demand of the country.

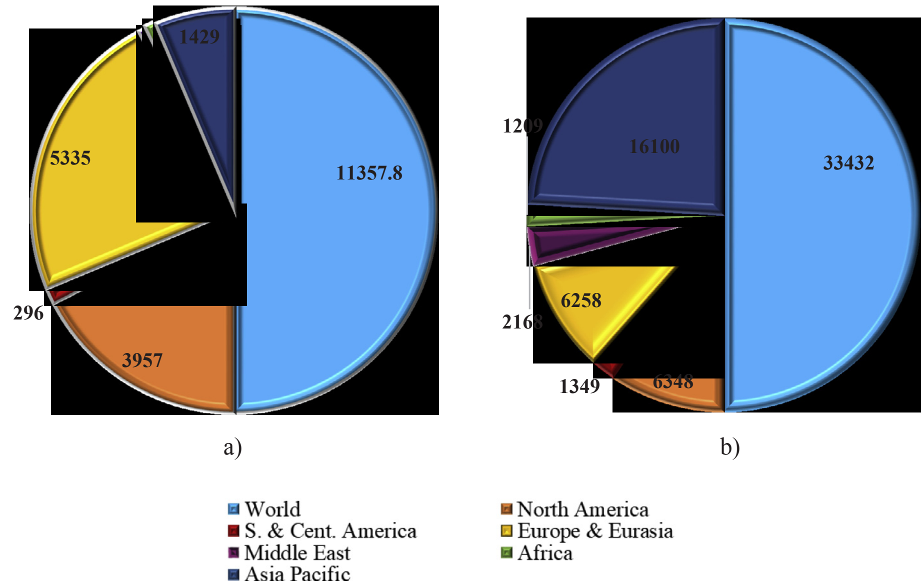


Fig. 2. CO_2 production (million tonnes) by region in: a) 1965, and b) 2016 (BP Statistical Review of World Energy, 2018).

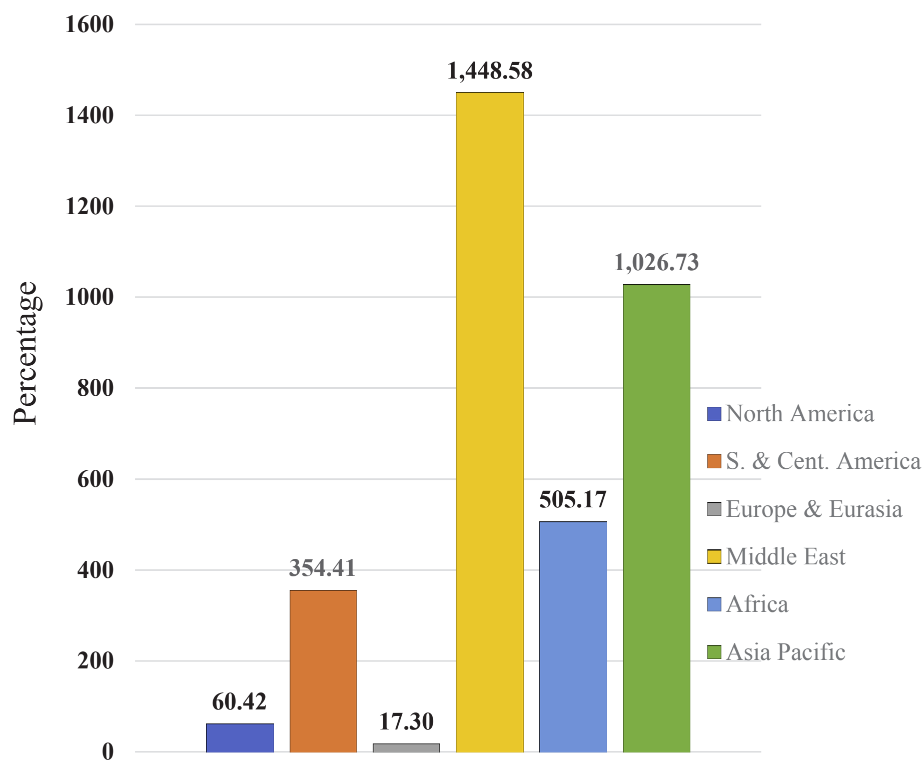


Fig. 3. Percentage increase in the values of CO_2 production from 1965 to 2016 by region (World carbon dioxide emissions, 2017).

In a numerical study regarding the wave energy resources of Shandong peninsula, east of China, it was noted that the mean significant wave height is 2.3 m and time-averaged wave power is 5.1 kWm^{-1}. Also, the largest wave power is 300 kWm^{-1}, corresponding to NE and NNE directions (Liang et al., 2013). The monthly-averaged wave power for various sites of the study area is illustrated in Fig. 7. As depicted in Fig. 7, the Chengshantou headland has the largest potential for a WEC. In an analysis of wave energy resources of China East adjacent seas (Bohai Sea, Yellow Sea and East China Sea), the two sites of Liaodong Peninsula Headland and East Zhoushan Island, were considered. For the latter, the autumn period was shown to have more wave energy, while winter has greater wave energy at Liaodong Peninsula Headland. As the significant wave heights for these areas are between 1 and 2 m and wave periods are 4–6 s, a careful selection of WECs is recommended to achieve the maximum efficiency for the mentioned ranges (Liang et al., 2014). In a thorough research study investigating the characteristics of the China Sea wave energy resources (Zheng et al., 2014), it was found that wave energy in South China Sea differs significantly in each season since as affected by the monsoon. Generally, the China Sea wave power increases gradually from March, April and May to December, January and February. The Luzon Strait is recognized as an area with considerable wave power of 30–40 kWm^{-1} in December, January and February; 21–27 kWm^{-1} in September, October and November; and, 6–10 kWm^{-1} in March, April and May (Zheng et al., 2014).

In a recent study by Mirzaei et al. (2015), the wave energy potential

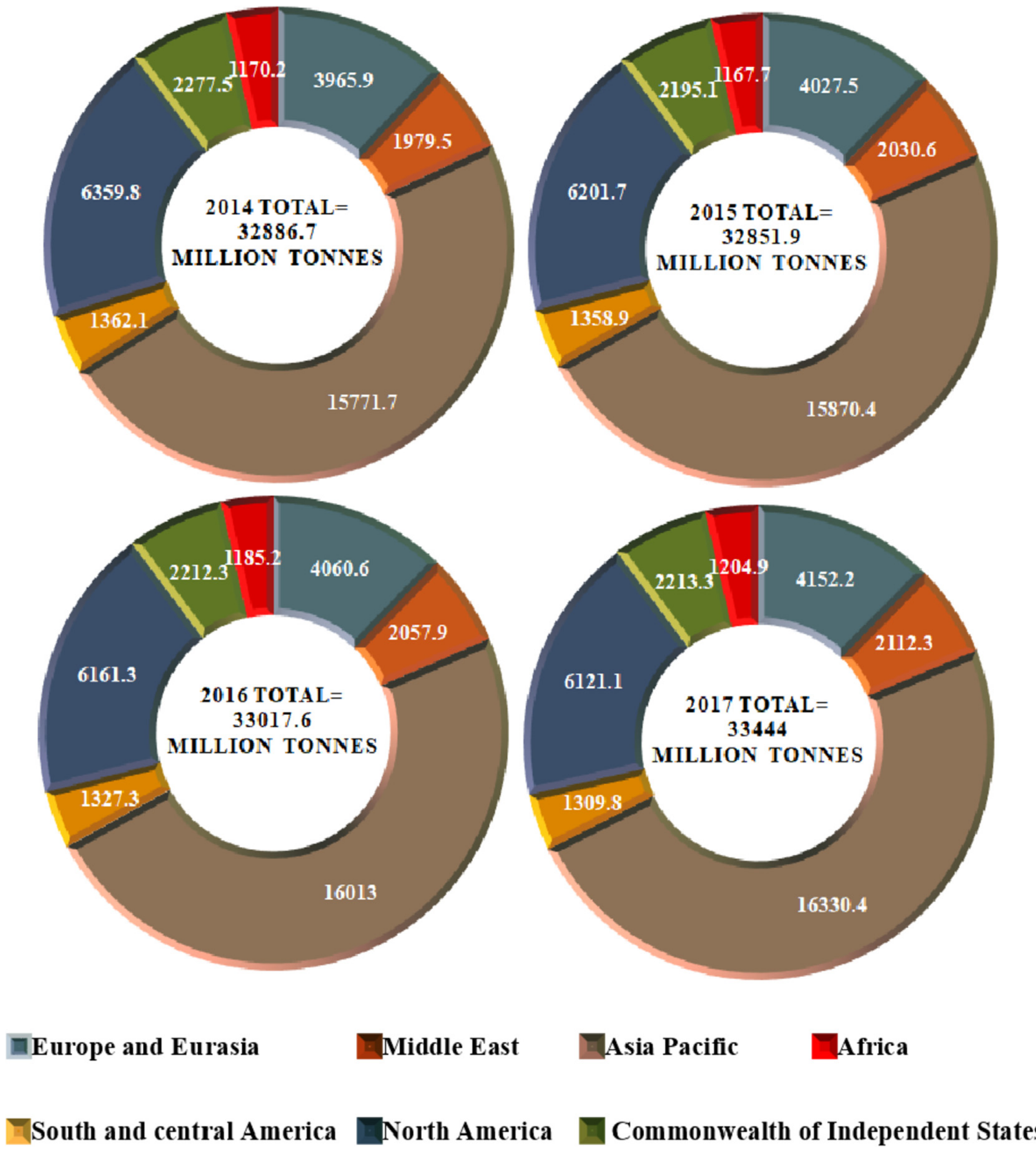


Fig. 4. CO_2 production from 2014 to 2017 by region (BP Statistical Review of World Energy, 2018).

in the South China Sea was assessed by employing a 31-year simulation of wave characteristics. The zone between the east coast of Vietnam and the west coast of Luzon was reported to have the highest annual wave power, with more than 20 kWm^{-1}, while the southern and western parts of this area present the lowest wave power, with less than 3 kWm^{-1}. Additionally, several potential sites for wave energy farming were examined to estimate the average electric power for both annual and six-monthly (from September to February) periods. The two most energetic sites are Hameau Mo and Spratly, with wave power of 40 kWm^{-1} and 15–22 kWm^{-1}, respectively (Mirzaei et al., 2015). In an appraisal of offshore wave energy resource in the East China Sea (Wu et al., 2015), it was indicated that the approximate value of averaged offshore wave power is 13 kWm^{-1}, corresponding to the sea states with significant wave heights between 1.5 m and 3.5 m and wave periods of 6 s–8 s. In a research study concerning the variation of wave power in the China Sea and adjacent waters, it was revealed that the China Sea experiences a noticeable overall increasing trend in wave power with a rate of 0.1–0.7 kWm^{-1}/year and a rate of 0.5–4.5 cm/year for significant wave height. This increasing trend is readily observable for the waters of the Dongsha Islands, Ryukyu Islands and Taiwan Strait and for the north section of the South China Sea (Zheng and Li, 2015).

2.1.2. Japan

Before March 2011, in which the Great East Japan Earthquake and Tsunami caused a nuclear disaster in Fukushima, nuclear power plants provided 27% of Japan's domestic power (Bricker et al., 2017). However, after this catastrophe, almost all nuclear power plants were shut down and the government started to import more fossil fuels to fill the energy gap (Komiyama and Fujii, 2017). Besides the lack of energy caused by the tsunami event, there are several reasons why Japan could consider expanding its renewable energy use, including the Kyoto Protocol (and the commitment to reducing 6% of the greenhouse gas emissions), the lack of hydrocarbon based natural resources, and the possibility of boosting the economy by alleviating the present severe dependence on imported oil, natural gas and coal (Bricker et al., 2017).

As an island country with abundant wave energy resources, and a pioneer with technology to harness useable power from ocean waves since 1970s, wave energy could be considered as a practical solution to generate power in Japan. Nevertheless, to the authors' knowledge, limited research has been carried out on wave resources in Japan.

Long-term trends of wave energy around Japan, based on data obtained from 1980 to 2009, indicated that the annual mean wave energy around Japan's shorelines to be 6.4 kWm^{-1}, with an increasing trend of

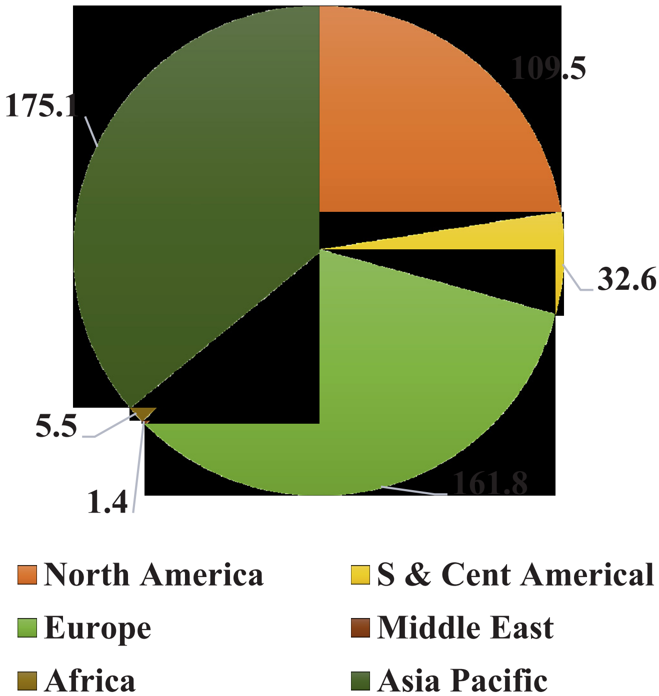


Fig. 5. Renewable energy consumption (MTOE) by region in 2017 (BP Statistical Review of World Energy, 2018).

0.27 kWm^{-1}/30-years (Sasaki, 2012). In an estimate of the wave power potential along the coastline of the entire country, it was found that between 36 GW and 50 GW is available, a value of the order of Japan's pre-2011 nuclear power generation capacity (Bricker et al., 2017). Moreover, the majority of this wave power is concentrated around the northeastern coast of Japan. Hence, constructing wave farms in this part of country is recommended.

In recent years, a few commercial and industrial activities have started regarding the manufacturing of commercial-scale WECs in Japan. To illustrate, on a jetty at the Port of Kobe a scaled WEC with 1.4 m in diameter that uses vertical movement of the waves to generate electricity was tested. The results obtained prompted the company to build the commercial-scale unit, which will be 14 m in diameter and have an estimated capacity of up to 1.2 MW (Japanese firm demonstrates floating wave prototype, 2017. Available from: < https://tidalenergytoday.com/2017/06/05/japanese-firm-demonstrates-floating-wave-prototype). In addition, a team of researchers at the Okinawa Institute of Science and Technology Graduate University aim to replace tetrapods (pyramid-like concrete structures designed to dampen the force of incoming waves and protect beaches from erosion, available in large number in Japan's beaches) with turbines designed to convert wave energy into electricity. The first prototype is going to be installed in the near future (Japanese scientists aim to turn ocean wave energy into electricity, 2017. Available from: https://www.upi.com/Science_News/2017/09/22/Japanese-scientists-aim-to-turn-ocean-wave-energy-into-electricity/8311506094368). Finally, it was reported by the NEDO Company that the world-first demonstration test of an oscillation water column (OWC) type wave power generation device that uses an impulse turbine to achieve a large output was successful in Japan in which an air turbine-based wave power generation system (rated power output: 15 kW) on the shoreline in the Port of Sakata was installed and generated the maximum power output of 13 kW (Focus NEDO, 2017. Available from: http://www.nedo.go.jp/content/100874638.pdf).

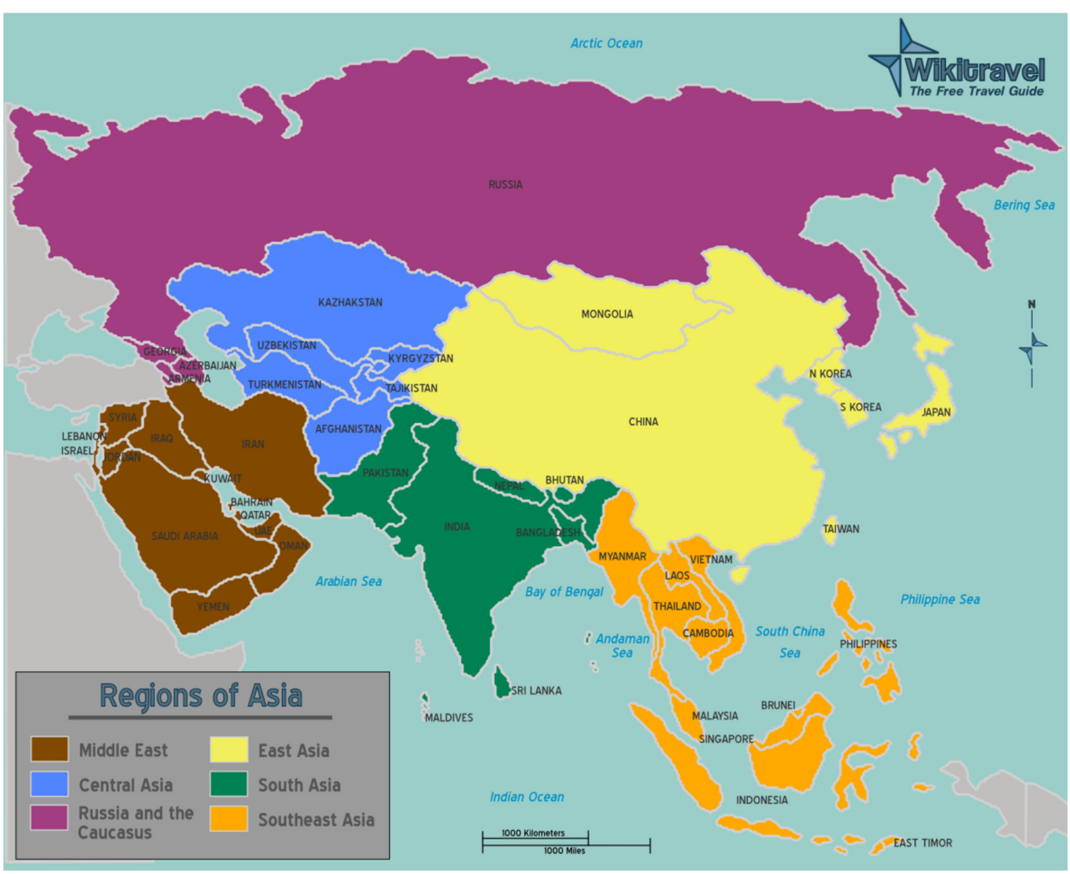


Fig. 6. Map of Asia and its regions (Available from: https://wikitravel.org/upload/shared//archive/a/a7/20080904032204%21Map_of_Asia.png).

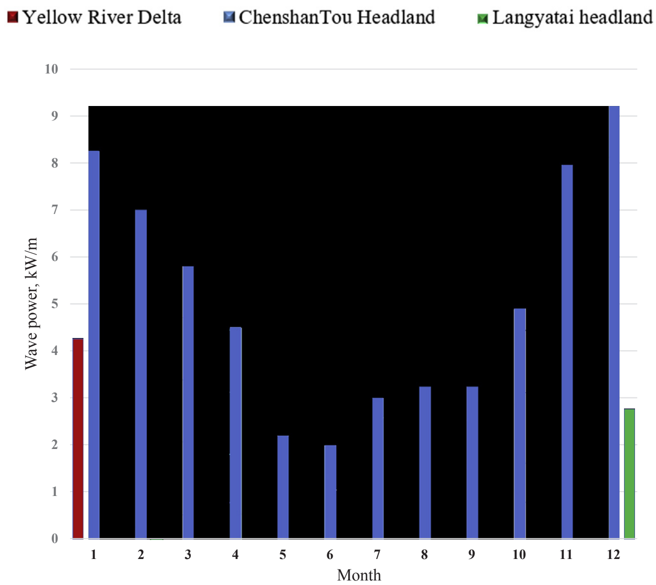


Fig. 7. The monthly-averaged wave power of three selected sites in Shandong peninsula, China (Redrawn from Liang et al., 2013).

2.1.3. Korea

Shin et al. (2014) predicts that if the current trend of climate change continues in Korea, then its temperature will rise by 4 °C and the amount of precipitation will increase by 21% in 2100 (Shin et al., 2014). The country relies on imports for 97% of its energy demands, known as one of the top ten countries in both energy consumption and carbon dioxide emission. Hence, the government is enacting strict policies to promote renewable energy (Shin et al., 2014). Since the country is a peninsula surrounded by the Yellow Sea, East China Sea and East Sea, capturing wave power can significantly contribute to an increase in electric power generation, the protection of the environment, and the economic growth of the country (Kim et al., 2012).

In an investigation of wave energy resources around the Korean peninsula by using hindcast wave data for 1979–2003, the wave power demonstrated a strong seasonality. For the southwestern, southern and eastern parts of peninsula, the annual mean wave powers are 11 kWm^{-1}, 4 kWm^{-1}, and 6 kWm^{-1}, respectively. The highest monthly-averaged wave power with value equals to 25 kWm^{-1} was observed on the southwestern side of the peninsula in winter, while it is 10 kWm^{-1} in summer (Kim et al., 2011). This higher wave energy is due to the northwestern seasonal monsoon, while the eastern coast is sheltered from the winter monsoon by the mainland (Kim et al., 2012). The spatial distribution of the seasonal average of wave power around the peninsula is depicted in Fig. 8.

Recently, a completed bottom-standing oscillating water column with a length of 37 m and width of 31.2 m, rated at 500 kW, is installed at Yongsoo, about 1 km off the coast of Jeju Island, South Korea (Falcão and Henriques, 2016). Also, a Finnish wave energy company (Wello) is collaborating with Korean companies on the construction of a wave energy power plant. The ultimate goal of this project is to develop a more profitable WEC technology with the assistance of local Korean expertise (Penguin to take the plunge in Korea, 2016. Available from: https://tidalenergytoday.com/2016/07/20/penguin-to-take-the-plunge-in-korea).

2.1.4. Taiwan

Taiwan Island is located in the South China Sea has an average annual growth of 3.7% in its energy consumption and an annual growth rate of CO_2 emissions of 5% (Chen and Lee, 2014). Since the country is vulnerable to rising sea levels as a result of climate change, the Taiwanese government is interested in reducing emissions through renewable energy resources (Kung et al., 2017). The country's climate is affected by monsoons in winter and typhoons in summer and hence, it enjoys abundant wave energy near the coastal area for all seasons, which can be regarded as a potential place for developing wave farms (Chiu et al., 2013).

In a study about the spatial and temporal characteristics of wave power density in Taiwan coastline, it was noted that wave energy resources in these coasts are dominated by monsoons. The peak wave power occurs in autumn and winter (maximum value in November and minimum in May and June) for all Taiwanese waters, except for the southwestern coast (Chiu et al., 2013). The medium-term and long-term schedules of technical development of wave energy in Taiwan are presented in Table 1. For offshore locations with substantial wave resource, the wave power reaches the value of 20–70 kWm^{-1}. On this basis, the northeastern side of Penghu Island in the Taiwan Strait is introduced to be the optimal place for wave energy generation due to its abundant northeasterly monsoon waves (Lin and Fang, 2012).

2.2. South Asia

South Asia has nearly a quarter of the global population. The countries analyzed in this sub-region are: Bangladesh, India, Maldives, and Sri Lanka (Fig. 6).

2.2.1. Bangladesh

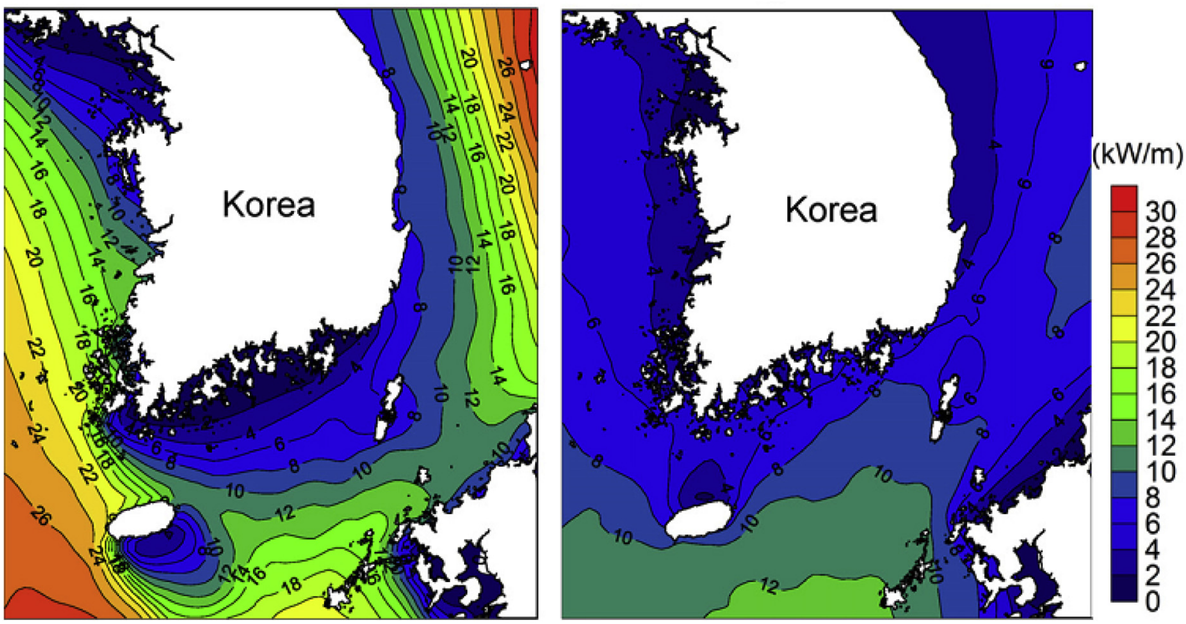
Bangladesh is a developing country with a total land area of 147,570 km^2. The country shares land borders with India and Myanmar, Nepal, and Bhutan, while its maritime territory in the Bay of Bengal is roughly equal to the size of its land area. With respect to accessibility of people to electricity, the country is far behind the world standard. Therefore, the government is determined to take immediate action and supply electricity to the nation by 2020. According to Bangladesh Policy of Renewable Energy (BPRE), 10% of the electricity generation from renewable sources should also be achieved by 2020 (Baky et al., 2017). To serve this purpose, the use of renewable energy attracted a significant attention among authorities, while the energy derived from oil, gas, and coal remain the dominant role in satisfying the growing demand (Hossain et al., 2017). As the country has 724 km of coastal line along the Bay of Bengal, it can harness the potential of wave energy to address the energy crisis problem especially for the island communities and remote coastal areas.

The feasibility study of wave energy utilizing OWC systems for three remote islands of Bangladesh (Sandwip, Kutubdia and Saint Martin) indicated that the most feasible solution for providing power to these deprived islands is to exploit wave energy. Wave power has the potential to play an important role in the socio-economic development of these coastal zones (Samrat et al., 2014b).

At Cox's Bazar, Chittagong, the wave energy resource assessment, economic conditions, challenges and the cost estimation for power generation were examined. Islam et al. (2016) found that wave power is higher than average from April to October, and particularly from November to March. Therefore, wave farms can be installed to supply the power demand of the area (Islam et al., 2016). In 2011, a Malaysian-based company has presented plans to establish a wave power plant in north Chittagong, with an output capacity of almost 900 million kWh, which in turn can assist the government to cut its electricity production cost by half (Wave-based power plant takes shape in Bangladesh, 2011. Available from: http://www.thedailystar.net/news-detail-193146). In another investigation concerning the Sandwip area, it was estimated that by spending 4 million USD, a sea wave farm can be constructed capable of generating 30 MW with limited ongoing maintenance costs (Fowze et al., 2012).

2.2.2. India

With a population of more than 1.3 billion, India is the fourth largest energy consumer globally. Energy consumption is increasing at a



(a) (b)

Fig. 8. The monthly-averaged wave power around the Korean seas in: (a) January; (b) August (Kim et al., 2012).

Table 1
Schedules of technical development of wave energy in Taiwan (Chen and Lee, 2014).

Medium-term (2020)	Long-term (2025)
✓ Applying 100 kW wave power generator units. ✓ Commercialization of 100 kW wave power generator with high efficiency. ✓ Grid connection technology.	✓ Having the latest technology to build commercial scale power plant. ✓ Conducting international marketing of wave power generation devices.

Table 2
Optimal locations for wave energy converters in India (Indian Renewable Energy Development Agency Limited (IREDA), 2014).

State	Location	Wave power (kWm^{-1})
Maharastra	Kudal	21.95
Kerala	Trivandrum	25.08
Tamil Nadu	Kanyakumari	23.39
Tamil nadu	Puducherry	10.59
Andhra Pradesh	Kaviti	14.96

fast rate, reaching 2280 BkWh by 2021–22, and approximately 4500 BkWh by 2031–32 (Tripathi et al., 2016). Several reasons have motivated the Indian Government to take advantage of renewable energy resources, including sparing fossil fuel reserves for coming generations, avoiding global warming, balancing the country's electricity demand and meeting the energy shortage (5.1 pc in 2014-15) (Jha and Puppala, 2017). Since the country has a long coastline (about 5423 km) with the Bay of Bengal and the Arabian Sea, and around 5.7 million waves per year, effective measures may be taken to harness this wave energy (Kumar and Anoop, 2015).

In an assessment of the wave power potential around the Indian shelf seas, it was found that along the western shelf seas there are seasonal variations in wave power, namely the October–January (post-monsoon) period, which has the lowest seasonal mean value, 2.6 kWm^{-1}, and the June–September period, which has the highest value, 25.9 kWm^{-1}. For the eastern part of India, the mean annual wave power is between 2.6 and 9.9 kWm^{-1}, which is lower than that of the western part (7.9–11.3 kWm^{-1}). In the southern area, the annual mean wave power has the highest value (11.3 kWm^{-1}) with the least seasonal variation in wave power and, hence, this area is considered the optimal region for a wave power plant (Kumar and Anoop, 2015).

In a report prepared by the Indian Renewable Energy Development Agency (2014), the wave energy potential along the Indian coast was explored in detail. According to their findings, higher wave power is available along the west coast, which is probably due to the strong waves during the south-west monsoon. However, the maximum wave power can be obtained at the southern tip of the Indian peninsula (Kanyakumari, Nagercoil district, Koodankulam) due to very strong winds prevailing in the region. Five potential sites suitable for the deployment of wave energy devices were determined based on wave statistics. These locations and their wave power are presented in Table 2.

2.2.3. Maldives

As a series of islands in the Indian Ocean composed of 26 ring-shaped atolls, the Maldives has a territory spanning about 300 square kilometers. Traditionally small diesel power plants are the primary energy sources for the country, causing power supply vulnerability, strong dependence on imported fossil fuels and emissions of greenhouse gases. In turn, this results in damaging impacts on tourism promotion (a key national industry) and sea level rise that threatens the existence of the country (Liu et al., 2018). The use of wave energy across the archipelago may thereby be taken into account as an effective strategy, but just a few studies have considered this possibility.

In a study conducted on wave energy across South Maalhosmadulu Atoll, it was found that there is a predictable alteration in monsoon winds, influencing the wave energy conditions across the atoll on a seasonal basis (Kench et al., 2006). In an assessment of wave around Malè and Magoodhoo Islands, the average wave power density in deep waters were reported to be between 8.5 kWm^{-1} in the north-eastern part to about 12.7 kWm^{-1} in the south-western region. Capturing this energy could make a substantial contribution to supply the power required for low-density population areas and help to produce fresh water which may assist the Maldives towards energy self-sufficiency

(Contestabile et al., 2017). To provide peak power potential of 2000 kW and desalination potential of 50 kL per day in Maldives, an Australian firm (Stonehenge Metals) plans to install a commercial wave farm around Hanimaadhoo Island (Stonehenge to harness Maldivian waves, 2015). The employed WEC system is based upon a point-absorber device, but consists of a series of small floating buoys. The number of buoys can be increased or decreased depending on power needs (Commercial wave energy operation to be established in the Maldives, 2015. Available from: https://www.hoteliermaldives.com/commercial-wave-energy-operation-to-be-established-in-the-maldives).

2.2.4. Sri Lanka

As an island country in the Indian Ocean with ample sunny days and strong wave and wind resources in many regions, Sri Lanka is an ideal candidate to almost generate its entire electricity by renewable resources (Kolhe et al., 2015; Wijayatunga, 2014). Regarding the utilization of wave energy, the power density is 20 kWm^{-1}, and the maximum wave height is less than 6 m, providing the country commercial energy potential (Watabe et al., 2001). In addition, it is found that wave energy power plants with capacity of 10 MW are electrically feasible for this region (Amarasekara et al., 2014). To achieve this goal, the Sri Lankan government has played a prominent leadership role by taking necessary initiatives and establishing energy policies to support investors and researchers. In this regard, Finland-based AW Energy has announced that the company plans to work with Sri Lankan authorities to assemble a project to harness the potential of wave energy around the southern coast of the country (Finland company to help Lanka produce wave energy, 2017. Available from: http://www.dailynews.lk/2017/10/11/local/130920/finland-company-help-lanka-produce-wave-energy). Also, an Israeli wave energy developer, WERPO, has secured a contract with the largest provider of electricity in Sri Lanka (Ceylon Electricity Board) to construct a 10 MW wave power plant, with 10 additional plants to follow (WERPO to make waves in Sri Lanka, 2015. Available from: < https://tidalenergytoday.com/2015/07/14/werpo-to-make-waves-in-sri-lanka).

2.3. Southeast Asia

Stretching between the northern and southern hemispheres, this region has a number of countries with considerable potential for wave energy development, e.g., Brunei Darussalam, Indonesia, Malaysia, and Vietnam (Fig. 6).

2.3.1. Brunei Darussalam

Brunei Darussalam is located between 4°N and 5.8°N latitude and 114.6°E and 115.4°E longitude in Southeast Asia on the north coast of the island of Borneo. Despite the fact that the country is a major producer of oil and gas, the Sultanate aims to diversify its energy portfolio and follow global trends in search of alternative renewable energy sources. This supports its power demand which is growing at a rate of 7–10% annually (Malik, 2011).

In an appraisal study to determine the potential of wave energy for Brunei Darussalam (Malik, 2011), December was found to be the month with the maximum monthly-averaged power, 487 kWm^{-1}, while the minimum generated power is 54 kWm^{-1} in April. As the country has a coastline of approximately 270 km, it can provide 15–126 GW, and hence, the yearly theoretical potential of the wave energy is 6.6×10^{11} W. The monthly mean potential of ocean wave power averaged over a period of six years are presented in Table 3. These data along with other wave energy statistics support the eligibility of this area for wave farm deployment (Mirzaei et al., 2015). However, it would appear that the country plans to remain dependent on fossil fuels until 2030 (Quirapas et al., 2015).

Table 3
Monthly mean wave power averaged over a period of six years (2003–2008) in Brunei Darussalam (Malik, 2011).

Month	Wave power (kWm^{-1})
January	467
February	314
March	185
April	54
May	88
June	67
July	114
August	122
September	129
October	151
November	270
December	487

2.3.2. Indonesia

Located between the Indian and Pacific oceans, Indonesia is the world's largest island country and the world's fourth most populous country. Over the past few years, the country's economy has experienced rapid growth at an average rate of 5.4% per year. This was followed by an increasing amount of total energy consumption and a growing tendency towards using fossil fuels. Therefore, a set of energy and environment-related domestic policies have been developed by the government as countermeasures to mitigate the environmental impacts of fossil fuel consumption, by exploiting renewable energy resources (Sugiawan and Managi, 2016). Since the country also has the fourth longest coastline globally, with a significant wave energy potential, it could construct wave power plants at various locations to supply electricity continuously to remote areas and thereby, respond to the increasing demand of energy (Ali and Hadi, 2016).

In an assessment of the wave energy resource around Indonesian seas, it was determined that areas with the most promising wave power are situated in the south of Java, south west of Sumatera, Bali, Nusa Tenggara Barat and Nusa Tenggara Timur, with significant average wave power of 40–60 kWm^{-1} (Ribal and Zieger, 2016). In another study, it was reported that areas around Java are one of the potential regions for wave energy projects in Indonesia, with January to December as the months with the most available wave power (Zikra, 2017).

In exhaustive research carried out by Indonesian Ocean Energy Association (2012), it was found that there is a theoretical wave power resource of 510 GW, with 10–35 MW per kilometer of coastline (Quirapas et al., 2015). On this account, an Australian private company (Bombora Wave Power) has signed a technology evaluation agreement with an Indonesian company (Anoa Power) to provide WECs. Rated at 1.5 MW, each of these devices is potentially able to supply renewable electricity for 500 homes or deliver 1 GL of desalinated water each year, comparable to the equivalent greenhouse gas benefit of taking 825 cars off the roads (Bombora Wave Power to supply wave power collectors to Indonesia, 2015).

2.3.3. Malaysia

Located in Southeast Asia, Malaysia has two distinct regions divided by the South China Sea, namely Peninsular Malaysia (West Malaysia) and Malaysian Borneo (East Malaysia). According to the latest statistics and figures released by the government, the predicted energy demand of the country will be more than 150,000 GWh, 1.5 times the demand in 2010, due to growing population, swift development and industrialization (Behrouzi et al., 2016). It has been reported that the Malaysian water regions have abundant potential for harnessing wave energy due to a strong northeast monsoon that generates high waves. In a survey on public acceptance of marine renewable energy in Malaysia, about 83% of respondents agreed with marine renewable energy projects and 63% emphasized that the government should be more supportive of research and development (R&D) to allow marine renewable energy to be implemented in the country (Lim and Lam, 2014).

In an analysis on wave power potential along the east coast of

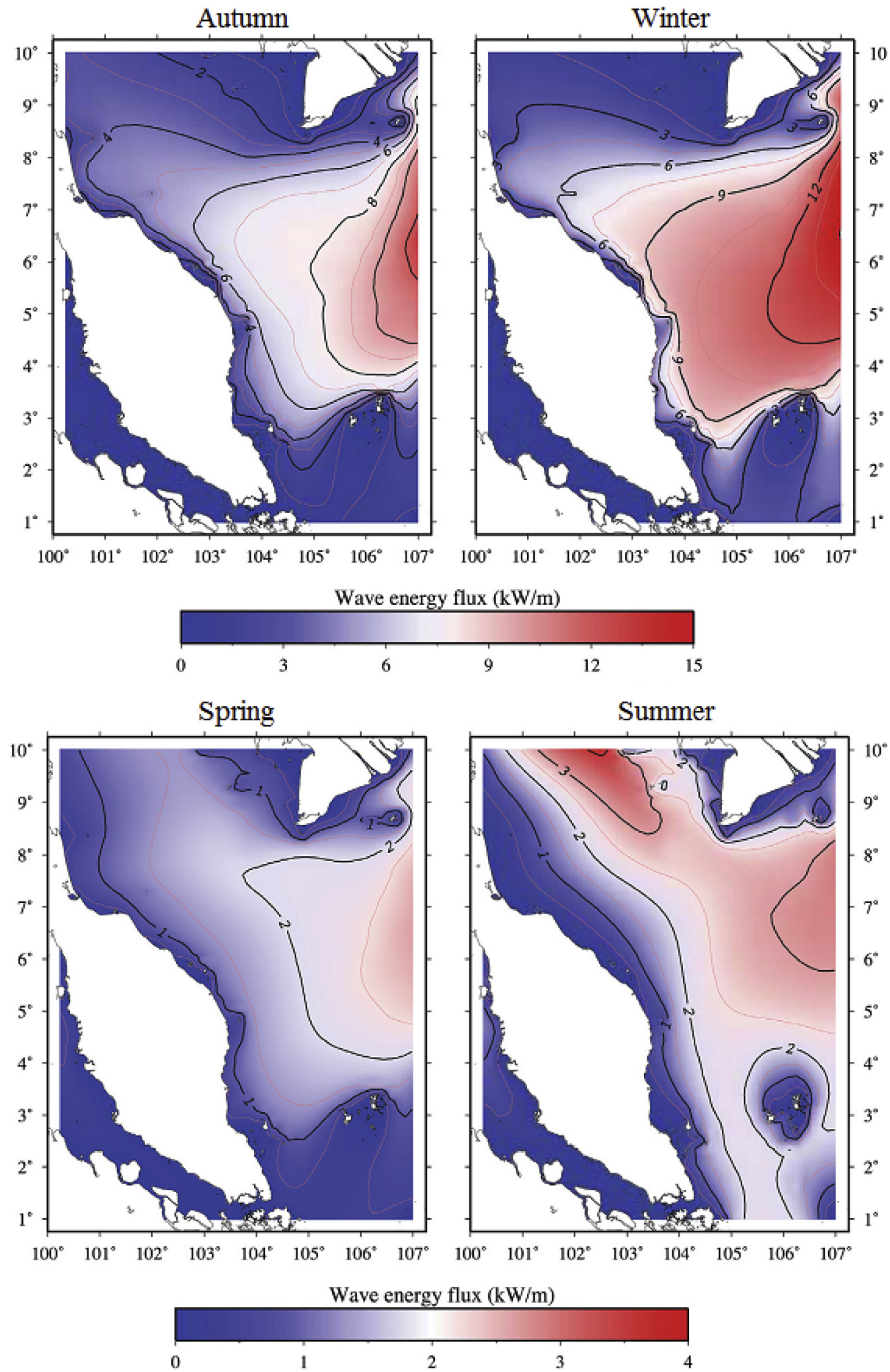


Fig. 9. The seasonal mean spatial distribution of wave energy flux in Peninsular Malaysia (Mirzaei et al., 2014).

Peninsular Malaysia, a strong fluctuation in seasonal wave power was found, with the highest wave power during the winter monsoon. Moreover, the wave climate is more energetic in the northern part of the country ($4\,kWm^{-1}$) than in the southern part ($2.5\,kWm^{-1}$). Based on the current efficiency of WECs, it is viable to harvest this wave resource, particularly in the northern region during the winter monsoon, as shown in Fig. 9 (Mirzaei et al., 2014). Further investigations on the feasibility of oscillating water column WECs in this coast is highly recommended (Chong and Lam, 2013). In addition, several wave energy hotspots are available as possible sites for wave farming such as Sarawak, Kota Kinabalu, Mabul Island, Pulau Mentagor Island, and Perhentian Island with expected average power output of $5\,kWm^{-1}$,

6.5 kWm^{-1}, 7.9 kWm^{-1}, 7 kWm^{-1}, and 15.9 kWm^{-1}, respectively (Samrat et al., 2014a).

2.3.4. Vietnam

As a developing country in Southeast Asia, Vietnam is managing high economic growth over the past decade, leading to an ongoing increase in the country's energy demand (15% per year) (Luong, 2015). This accelerating trend makes is inevitable for the government to reinforce its tendency towards placing more reliance on renewable energy sources by increasing the share of these sources to 5% and 11% of the total primary energy consumption by 2020 and 2050, respectively (Luong, 2015). Since Vietnam is located in a monsoonal climate zone and has a coastline of about 3000 km, it has significant potential for wave energy development. However, this resource is currently not being utilized within the East Sea.

It is worth noting that the potential for wave power is very promising, especially in the Central part and the Vietnamese islands. Recently, several potential sites for wave energy farming have been identified including Truong Sa (Khanh Hoa), Phu Quy (Binh Thuan), Cu Lao Cham (Quang Nam), Con Co (Quang Tri), and Hon Me (Thanh Hoa) (Quirapas et al., 2015). The Truong Sa Island is reported to have the highest wave energy in the entire East Sea which is due to the two seasons of northeast monsoon and southwest monsoon. Moreover, according to a commercial study (Taking advantage of wave energy in Truong Sa Islands, 2012), the northeast of the island is the most suitable place to install WECs, and the most suitable converter for this region would be an improved Powerbuoy device designed by Uppsala University, Sweden.

2.4. West Asia

This region corresponds approximately to the Middle East minus Egypt. The countries with potential for wave power development are Azerbaijan, Iran, Lebanon, and Saudi Arabia (Fig. 6).

2.4.1. Azerbaijan

Azerbaijan, also called the Republic of Azerbaijan, is located in the south region of Eurasia and borders with Russia to the north, the Caspian Sea to the east, Armenia to the west, Georgia to the northwest and Iran to the south. The country's economy is experiencing its post-Soviet transition, entering into a state-based oil economy. Two thirds of Azerbaijan is rich in oil and natural gas, and resources are the leading contributor of its economy. As such, declines in crude oil prices can exert adverse effects on the economy of the country. For the first time in the past few decades, the economy of the country has stagnated, forcing the government to search for alternative strategies for its sustainable development through the potential of renewable energy resources, among which wave energy is a promising option (Vidadili et al., 2017). While the country has a coastline of about 800 km with the Caspian Sea, with considerable wave power available, only one study has examined the possibility of extracting this energy.

Since the Caspian Sea has the potential to produce harvestable wave energy, it was found that installing WECs off Absheron Peninsula (where Baku is located, the capital and most populous city of the country) would be advantageous from a technical and economic perspective. This is due to the fact that in the northern coast of this peninsula, the average wave height is 1.5–2.5 m, and for the southern region it is 1–2 m, while the significant wave height sometimes reaches 8–10 m (Mammadov, 2017). Based on the wave characteristics of this region, it has been reported that OWC devices would be the most effective energy converter to be employed (Mammadov, 2017). This type of converter can also be applied to supply the energy required in oil and gas platforms on the sea. The initial assessment of the potential energy in Absheron Peninsula revealed that wave energy devices with 10–20 kW installed power are the most appropriate units to be applied in this area (Mammadov, 2017).

2.4.2. Iran

Located in the Middle East, Iran has a total area of 1.65 million km^2 and a population over80 million people. The country has the second largest natural gas reserves and the fourth largest crude oil reserves in the world (Khojasteh et al., 2016; U.S. Energy Information Administration (EIA), 2018). Although fossil-based energy sources play the leading role in supplying the country's energy demand, there are several reasons why Iran should take advantage of renewable and sustainable energy resources, including a growing population and increasing energy demand, extreme air pollution in metropolitan areas, and adhesion to the Kyoto Protocol (Khojasteh et al., 2018; Mollahosseini et al., 2017). Iran borders with the Persian Gulf and the Oman Sea from south (with a coastline of about 2440 km), and the Caspian Sea with a 740 km coastline from the north (Khojasteh and Kamali, 2017; Tofigh and Abedian, 2016). While these seas have significant wave energy potential, to increase the share of renewable energies, they have not received sufficient legislative or commercial attention so far (Alamian et al., 2014; Khojasteh, 2015).

A comprehensive review on the wave energy potential of Iran was conducted by Khojasteh et al. (2018) to consider the possibility of installing WECs and finding wave energy hotspots. On this basis, it was found that the average and maximum wave power of the Caspian Sea, as the largest lake on Earth, are 14 kWm^{-1} and 30 kWm^{-1}, respectively. Moreover, point absorber systems were suggested as the most appropriate units to be applied in this sea (Alamian et al., 2014). The central region of the Caspian Sea has the greatest wave energy potential, especially in winter, with significant wave heights and wave power reach of 6 m and 100 kWm^{-1}, respectively (Rusu and Onea, 2013). A few wave energy hotspots have been suggested for wave power plants including Babolsar, Anzali Port and Tonekabon (Hadadpour et al., 2014; Khojasteh and Kamali, 2016). The monthly variation of the wave power distribution in southern Caspian Sea, where it borders Iran, is illustrated in Fig. 10. According to this figure, September to November has the highest wave power values, while the lowest values are observed during April to August. It also supports the theory that the mean wave power is higher in the central areas of the southern Caspian Sea during almost all months (Kamranzad et al., 2016).

The energy demands of people who live in remote, deprived and inaccessible areas around the Persian Gulf and the Oman Sea (with average powers of 16.6 kWm^{-1} and 12.6 kWm^{-1}, respectively) may be satisfied by wave power available at these areas (Zabihian and Fung, 2011). To serve this purpose, there are a number of wave energy hotspots in these seas for wave farm consideration, among which include Chabahar Port, Boushehr, Assalouyeh and Khowr-e Musa Bay. Based on the wave characteristics and climate conditions of these places, bottom-fixed heaving buoys, single point absorbers and attenuator systems are suggested as WECs (Rashid and Hasanzadeh, 2011; Saket and Etemad-Shahidi, 2012).

2.4.3. Lebanon

As one of the smallest country in Asia, Lebanon covers 10,230 km^2 of land. The economy of the country is gradually shifting from agricultural exports towards the manufacturing and tourism sectors. This phenomenon has aroused concern about the sustainability of the current energy status patterns and energy security. To address this issue, a National Renewable Energy Action Plan was organized by the Lebanese Ministry of Energy to produce 12% of the required energy from renewable resources by 2020 (Taher, 2017). While the country has a coastline of 225 km, with the Mediterranean Sea to its west, only limited literature is available to shed light on its wave energy prospects.

The wave energy potential of the Eastern Mediterranean Levantine Basin near Lebanon was recently explored. Despite the fact that a relatively low amount of wave energy was found in this region, wave power is exploitable due to its stable nature (with relatively small fluctuations) all year round (Zodiatis et al., 2014). The wave energy potential at three hotspots of Lebanon was also analyzed: a site in

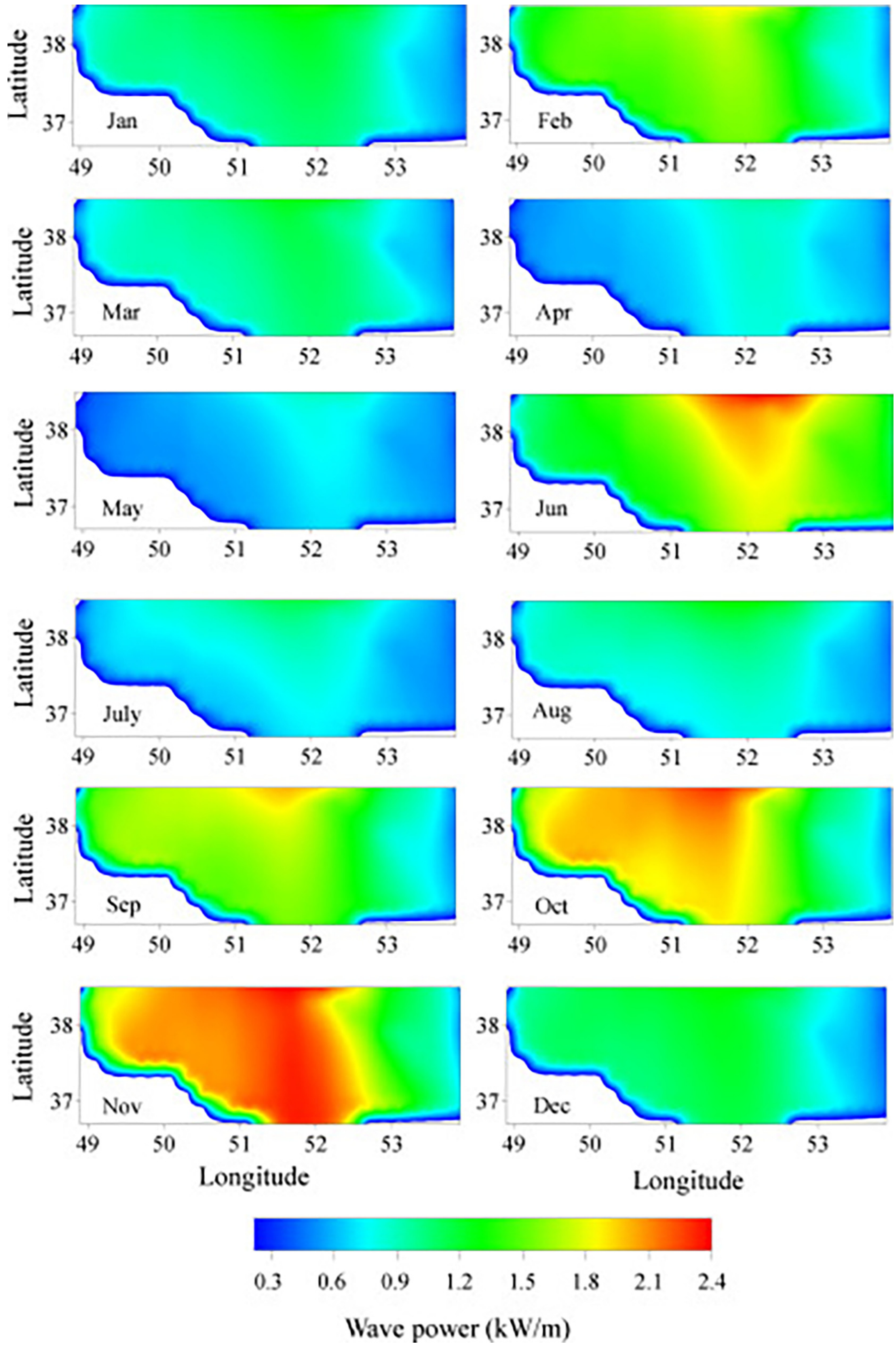


Fig. 10. The monthly mean wave power distribution in southern Caspian Sea (Kamranzad et al., 2016).

southern Lebanon, a wave buoy location off the coast of Beirut, and a site in northern Lebanon. It was reported that the stable value of wave power is approximately 9.6 kWm^{-1} (Aoun et al., 2013).

2.4.4. Saudi Arabia

As the world's largest crude oil exporter, the Kingdom of Saudi Arabia has embarked on a renewable energy program with a focus on reducing dependency on fossil fuels and create a sustainable energy future for generations, in particular those who reside in rural areas

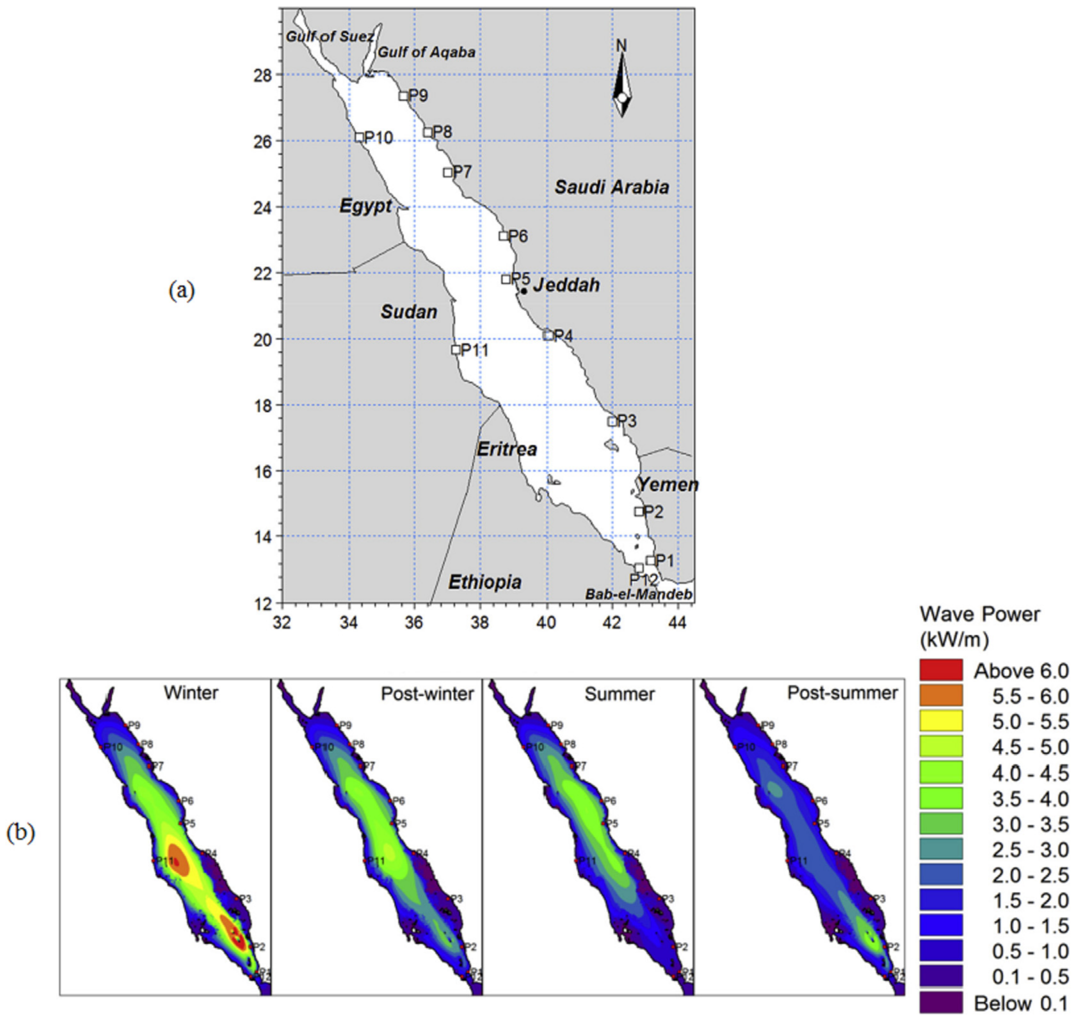


Fig. 11. (a) Selected coastal locations of Saudi Arabia in the Red Sea (P3−P9); (b) spatial distribution of seasonal mean wave power for these sites (Aboobacker et al., 2017).

(Demirbas et al., 2017). It is the only nation that has borders with the Red Sea coast and the Persian Gulf coast, and hence, the country can take advantage of capturing wave power. Regarding the Persian Gulf, it has been described in the section about Iran. The waters of this region have average powers of 16.6 kWm^{-1}, an amount which can be extracted by suitable wave energy absorbers.

There are insufficient studies on wave energy potential in the offshore and nearshore waters of the Red Sea (only two investigations are presented here). It was discovered by Aboobacker et al. (2017) that the deep waters of this sea have a long-term mean wave power of 4.5 kWm^{-1}. Seasonal variations in maximum wave power and location exist. To illustrate, winter has the highest wave power of 6.5 kWm^{-1} in the central and southern Red Sea, whereas summer and post-summer has average wave power of 4.5 kWm^{-1} in the central Red Sea and lower part of its northern region. On monthly basis, December–March have the highest mean wave power, while July–August present the lowest values (Aboobacker et al., 2017). Fig. 11 indicates some selected coastal sites in Saudi Arabia along with their seasonal mean wave power. In addition, since the Red Sea is rich in wind energy, the perspective of hybrid wind-wave projects should be prioritized (Langodan et al., 2016).

3. Conclusions

The rapid economic growth in Asia is accompanied by rising energy demand. Given the adverse environmental repercussions of fossil fuel consumption and the fact that most Asian countries are signatories of the Paris Treaty, there is considerable interest in the region in the development of renewable energy sources, including wave energy. In this work the wave energy resource and the potential for wave energy development in Asia were reviewed based on the available literature.

The wave energy resource was found to vary significantly between countries. This is not surprising given the geographical variety of Asia – from the shores of the Mediterranean (Lebanon) to Japan, Asian coastlines are exposed to very different climates and, as a result, wave power as a renewable energy source is more attractive in certain areas than in others. This variety was reflected in the present review, organized by sub-regions: East, South, Southeast and West Asia. The areas with the greatest potential for the development of wave farm projects were also presented.

The average values of wave power and the wave energy hotspots or areas suggested for wave energy development in each country are presented in Table 4. This may assist researchers, investors and policymakers in comparing different sub-regions and understanding the gaps in the current knowledge of the resource in Asia, while motivating and directing them for further studies and investments. The main conclusions for the four subregions are presented below.

In East Asia, China is poised to play a major role in the development of wave energy worldwide, with intense R&D efforts and a number of projects under way. Detailed data on the resource and, in particular, field data are handled by the Chinese authorities and not publicly available. In Japan the northeast coast is recommended for wave energy

Table 4
Average wave power and wave energy hotspots or development areas suggested in the literature.

	Country	Average wave power (kWm^{-1})	Wave energy hotspots/ suggested development areas
East Asia	China	5–40	• Chengshantou headland • Luzon Strait • Hameau Mo • Spratly • Dongsha Islands • Ryukyu Islands
	Japan	6.5	• Port of Kobe
	Korea	4–11	• Jeju Island • South and southwest coastlines
	Taiwan	20–70	• Penghu Island
South Asia	Bangladesh	Not defined.	• Chittagong
	India	2.6–11.3	• Southern and western coasts
	Maldives	8.5–12.7	• Malè and Magoodhoo Islands
	Sri Lanka	20	• Southern coast of the country
Southeast Asia	Brunei Darussalam	54–487	Not defined.
	Indonesia	40–60	• Areas around Java Island
	Malaysia	5–16	• Perhentian Island • Mabul Island
	Vietnam	Not defined.	• Truong Sa • Phu Quy • Cu Lao Cham • Con Co • Hon Me
West Asia	Azerbaijan	Not defined.	• Absheron Peninsula
	Iran	12.6–30	• Anzali Port • Babolsar • Tonekabon • Chabahar Port • Assalouyeh • Khowr-e Musa
	Lebanon	9.6	• Southern and northern parts
	Saudi Arabia	4.5–16.6	• Central parts of Red Sea

developments in view of its large resource. The country was a pioneer in wave energy, and renewed interest has arisen after the Fukushima nuclear disaster of 2011. In South Korea the southwestern coast of the peninsula is the optimum area from the point of view of the resource. There exist some local wave energy companies, and contacts with foreign companies have been established (e.g., Wello from Finland). Finally, the wave energy sector in Taiwan is still in its infancy, despite a considerable wave resource.

In South Asia, India stands out in the development of the wave energy sector. Due to the south-west monsoon, the west coast of the country is the area with the greatest resource. An in-depth study was conducted by the government in 2014. Despite significant contributions in the past, notably in the field of OWC and through academic institutions, no active projects are reported in the literature at present. As for the Maldives, the country consists of a great number of islands, which rely on expensive, polluting diesel generators for their electricity supply. Wave power can play a significant role in supplying energy to these remote islands. In Sri Lanka, the government has taken steps to implement practical wave energy projects, and contracts with foreign wave energy companies have been signed. In Brunei Darussalam there is a large wave energy potential; however, more research is necessary to quantify this potential. In Indonesia the average wave power is substantial in many areas, including the south of Java, the southwest of Sumatera, Bali, Nusa Tenggara Barat and Nusa Tenggara Timur. Further work to exploit this potential is required. In Malaysia the reported wave power is not significant, and therefore further studies should be carried out to determine whether or not wave energy is economically feasible in the country. As for Vietnam, the country has long coastlines but the resource has not been fully assessed and the wave energy sector has not begun to develop yet.

In West Asia, research has been carried out into the wave resource in Iran and Lebanon. Iran has areas with some potential, and a number of wave energy hotspots have been reported in the literature, alongside recommended WECs. Lebanon has average wave power, but its relative stability (with less marked peaks than in other regions) renders it attractive. Although no active projects in wave energy have been reported so far, the country is committed to increasing the share of renewables to 12% of its energy mix by 2020.

As a final conclusion, future research is necessary to better characterize the wave resource in many areas of the continent, and more investment is needed for commercial wave farms to be deployed and reduce the dependency of Asian countries on fossil fuels.

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